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Cooling rate of thermal electrons by electron impact excitation of fine structure levels of atomic oxygen

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Abstract. The atomic oxygen fine structure cooling rate of thermal electrons based on new effective collision strengths for electron impact excitation of the ground-state ^{3}P fine-structure levels in atomic oxygen have been fitted to an analytical expression which is available to the researcher for quick reference and accurate computer modeling with a minimum of calculations. We found that at the F region altitudes of the ionosphere the new cooling rate is much less than the currently used fine structure cooling rates (up to a factor of 2–4), and this cooling rate is not the dominant electron cooling process in the F region of the ionosphere at middle latitudes.

Key words. Atmospheric composition and structure (thermosphere – composition and density) · Ionosphere (mid-latitude ionosphere; modelling and forecasting).

1 Introduction

The electron temperature in the ionosphere is of great significance in that it usually controls the rates of many physical and chemical ionospheric processes. The theoretical computation of electron temperature distribution in the ionosphere requires the knowledge of various heating and cooling rates, and heat transport through conduction. Schunk and Nagy (1978) have reviewed the theory of these processes and presented the generally accepted electron cooling rates. Pavlov (1998a, c) has revised and evaluated the electron cooling rates by vibrational and rotational excitation of N_2 and O_2 and concluded that the generally accepted electron cooling rates of Prasad and Furman (1973) due to the excitation of $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g^+)$ are negligible in comparison with those for vibrational excitation of O_2.

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The thermal electron impact excitation of the fine structure levels of the ^3P ground state of atomic oxygen is presently believed to be one of the dominant electron cooling processes in the F region of the ionosphere (Dalgarno and Degges, 1968; Hoegy, 1976; Schunk and Nagy, 1978; Carlson and Mantas, 1982; Richards *et al.*, 1986; Richards and Khazanov, 1997). To evaluate the energy loss rate for this process, Dalgarno and Degges (1968) have employed the theoretical $O(^3P)$ excitation cross sections given by Breig and Lin (1966). The electron cooling rates of Hoegy (1976) and Carlson and Mantas (1982) which are currently used in models of the ionosphere are based on the excitation cross sections calculated by Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976). The shortcomings of the theoretical approach of Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976) were summarised by Berrington (1988) and Bell *et al.* (1998) Bell *et al.* (1998) improved the work of Berrington (1988) and presented the numerical calculations of the rate coefficient of this electron cooling rate for the electron temperature, $T_e = 200$, 500, 1000, 2000, and 3000 K and the neutral temperature, $T_n = 100$, 300, 1000, and 2000 K. The primary object of this study is to use the theoretical $O(^3P)$ excitation cross sections of Bell *et al.* (1998) to calculate and to fit to a new analytical expression for atomic oxygen fine structure cooling rate of thermal electrons.

2 The electron cooling rate by electron impact excitation of fine-structure levels of atomic oxygen

The $O(^3P)$ ground state is split into three fine structure levels $^3P_i\,(i = 2, 1, 0)$ with the level energies given by Radzig and Smirnov (1980) as $E_2 = 0$, $E_1 = 227.7\,\mathrm{K}$ (or 0.01962 eV), and $E_0 = 326.6\,\mathrm{K}$ (or 0.02814 eV). Collisions of thermal electrons with the ground state of atomic oxygen produce transitions among the $O(^3P_i)$ fine structure levels and the electron cooling. Sharma *et al.* (1994) found that within an accuracy of 1–2% the fine structure levels are in local thermodynamic equilibrium at the local neutral atom translation temperature, T_n, for altitudes up to 400 km:

$$\left[\mathrm{O}(^3P_i)\right] = [\mathrm{O}]D^{-1}\, g_i \exp\left(-E_i\, T_n^{-1}\right) \ , \tag{1}$$

where $g_i = 2i + 1$ is the statistical weight of the i-th level, $D = \sum_{i=0}^{2}(2i+1)\exp\left(-E_i\, T_n^{-1}\right)$, [O] is the full number density of atomic oxygen.

This study has been also conducted assuming that the velocity distribution of electrons is described by a Maxwellian distribution with a thermal electron gas of temperature, T_e. In this approximation the oxygen fine structure cooling rate is given by the expression (1) of Stubbe and Varnum (1972) as

$$L = \mathrm{N}_e[\mathrm{O}]D^{-1}\sum_{i=1}^{2}\sum_{j<i} S_{ij}\left\{1 - \exp\left[E_{ij}\left(T_e^{-1} - T_n^{-1}\right)k^{-1}\right]\right\} \ , \tag{2}$$

where

$$S_{ij} = g_i \exp\left[-E_i(kT_n)^{-1}\right]E_{ij}\left\{8k\,T_e(\pi\, m_e)^{-1}\right\}^{0.5} \times \int_0^{\infty} \sigma_{ij}(x)x\exp(-x)dx \ , \tag{3}$$

k is Boltzmann's coefficient, the $i = 2$ ground level with $E_2 = 0$ and the $i = 1$ level with $E_1 = 0.01962$ eV of $\mathrm{O}(^3P_i)$ are excited by thermal electrons, the $\mathrm{O}(^3P_j)$ deexcitation levels are the $j = 0$ upper level with $E_0 = 0.02814$ eV and the $j = 1$ level, $E_{ij} = E_j - E_i > 0$, $x = E(kT_e)^{-1}$, E is the energy of electrons, and m_e denotes the mass of electrons, σ_{ij} is the cross section for excitation by electrons of $\mathrm{O}(^3P)$ from i-th to j-th state.

It should be noted that deexcitation ($j \rightarrow i$) cross sections of $\mathrm{O}(^3P)$ are related with excitation ($i \rightarrow j$) cross sections of $\mathrm{O}(^3P)$ through the principle of detailed balancing. As a result, the excitation term of the electron cooling rate is defined as $\mathrm{N}_e[\mathrm{O}]D^{-1}\sum_{i=1}^{2}\sum_{j<i} S_{ij}$, and the deexcitation term of the electron cooling rate is $\mathrm{N}_e[\mathrm{O}]D^{-1}\sum_{i=1}^{2}\sum_{j<i} S_{ij}\exp\left[E_{ij}\left(T_e^{-1} - T_n^{-1}\right)k^{-1}\right]$. It follows from this definition of the cooling rate that in the energy balance equation for electrons, the cooling rate is subtracted from the electron heating rate received by thermal electrons from photoelectrons. The value of L is positive when $T_e > T_n$ and negative when $T_e < T_n$.

The cross section, $\sigma_{ij}(E)$, for the transition $i \rightarrow j$ is obtained from the collision strength, $\Omega_{ij}(E)$, by (see Eq. 1 of Hoegy, 1976)

$$\sigma_{ij}(E) = \pi a_0^2\, R_y\, \Omega_{ij}(E)(g_i\, E)^{-1} \ , \tag{4}$$

where a_0 is the Bohr radius, and R_y is the Rydberg constant. Using Eq. (4), we conclude that

$$S_{ij} = \pi a_0^2 R_y\left\{8(k\, T_e\, \pi\, m_e)^{-1}\right\}^{0.5} E_{ij}\, Q_{ij}(T_e)\exp\left(-E_i\, T_n^{-1}\right) \ , \tag{5}$$

where the effective collision strength, $Q_{ij}(T_e)$, is determined as

$$Q_{ij}(T_e) = \int_0^{\infty} \Omega_{ij}(x)\exp(-x)\mathrm{d}x \tag{6}$$

Carlson and Mantas (1982) found that the collision strengths calculated by Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976) can be approximated by the empirical formula

$$\Omega_{ij}(E) = A_{ij}\exp(-G_{ij}\, E) + B_{ij} + C_{ij} \ , \tag{7}$$

where the constants A_{ij}, B_{ij}, C_{ij}, and G_{ij} are given in Table 1 of Carlson and Mantas (1982).

In the approximation of Eq. (7) the effective collision strength is calculated as

$$Q_{ij}(T_e) = C_{ij} + kT_e B_{ij} + A_{ij}(1 + kT_e\, G_{ij})^{-1} \tag{8}$$

Figure 1 shows the effective collision strengths for the fine structure transitions $2 \rightarrow 1$ (left panel), $2 \rightarrow 0$

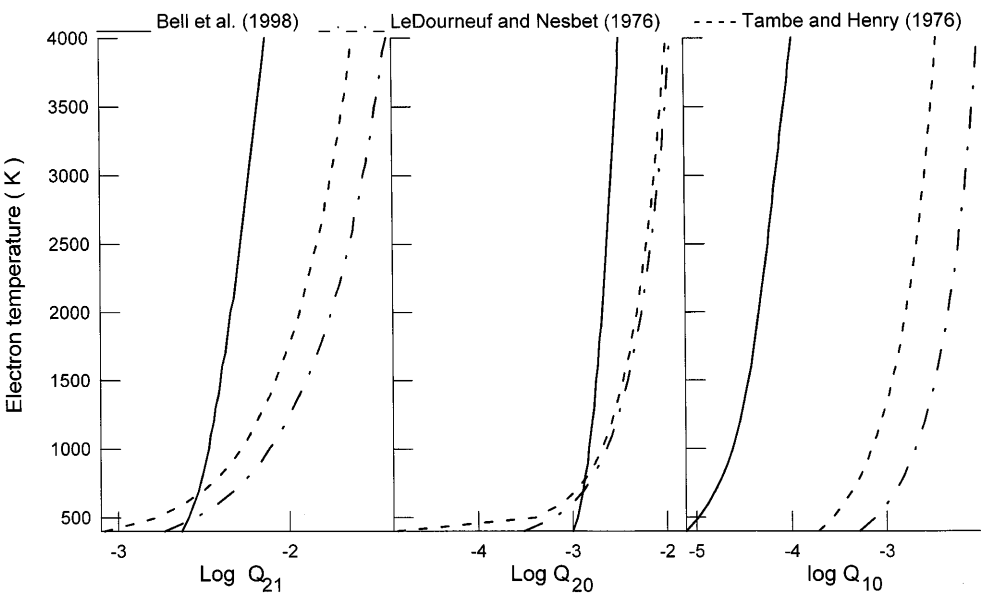

Fig. 1. Comparison of the effective collision strengths for the fine structure transitions $2 \rightarrow 1$ (*left panel*), $2 \rightarrow 0$ (*middle panel*), and $1 \rightarrow 0$ (*right panel*). *Solid lines* are $Q_{ji}(T_e)$ calculated by Bell *et al.* (1998). *Dashed-dotted lines* and *dashed* are $Q_{ji}(T_e)$ of Le Dourneuf and Nesbet (1976) and Tambe and Henry (1974, 1976) calculated in the approximation of Eq. (8) with the constants A_{ji}, B_{ji}, C_{ji} and G_{ji} given in Table 1 of Carlson and Mantas (1982)

(middle panel), and $1 \rightarrow 0$ (right panel). Solid lines on Fig. 1 show $Q_{ij}(T_e)$ given by Bell *et al.* (1998). The values of the effective collision strengths of Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976) calculated in the approximation of Eq. (8) are shown in Fig. 1 as dashed and dashed-dotted lines, respectively. It is evident that the effective collision strengths of Le Dourneuf and Nesbet (1976) and Tambe and Henry (1974, 1976) are much larger than those obtained by Bell *et al.* (1998) at the F region altitudes of the ionosphere where $T_e > 1000$–1500 K. These results show the importance of the use of the effective collision strengths of Bell *et al.* (1998) instead of those from Le Dourneuf and Nesbet (1976) or Tambe and Henry (1974, 1976) in calculations of the oxygen fine structure cooling rate.

3 Analytical expressions

To use the numerical results of Bell *et al.* (1998) in calculations of the electron cooling rate by excitation of oxygen fine structure we obtained analytical expressions, $Q^*_{ij}(T_e)$, for $Q_{ij}(T_e)$ available to the researcher for quick reference and accurate computer modelling with a minimum of calculations as

$$Q^*_{21}(T_e) = 1.10 \cdot 10^{-4} T_e^{0.5} \quad , \tag{9}$$

$$Q^*_{20}(T_e) = 4.90 \cdot 10^{-5} T_e^{0.5} \quad , \tag{10}$$

$$Q^*_{10}(T_e) = 1.12 \cdot 10^{-8} T_e^{1.1} \quad , \tag{11}$$

where the unit of T_e is K.

The value of maximum error for the effective collision strength may be evaluated as $\delta_{ij} = \max\left|1 - Q^*_{ij}(T_e)/Q_{ij}(T_e)\right|$. We found that $\delta_{21} = 0.08$, $\delta_{20} = 0.06$, and $\delta_{10} = 0.07$ within the electron temperature range 400–4000 K and this accuracy is enough to reproduce the value of L given by Eq. (2).

Using the analytical expressions (9)–(11) for the effective collision strengths one obtains:

$$S_{21} = 1.863 \cdot 10^{-11}, \mathrm{eV\,cm^3\,s^{-1}} \quad , \tag{12}$$

$$S_{20} = 1.191 \cdot 10^{-11}, \mathrm{eV\,cm^3\,s^{-1}} \quad , \tag{13}$$

$$S_{10} = 8.249 \cdot 10^{-16} T_e^{0.6} \exp(-227.7\, T_n^{-1}), \mathrm{eV\,cm^3\,s^{-1}} \quad , \tag{14}$$

$$\begin{aligned} L = {} & \mathrm{N}_e[\mathrm{O}] D^{-1} \big(S_{10}\{1 - \exp[98.9(T_e^{-1} - T_n^{-1})]\} \\ & + S_{20}\{1 - \exp[326.6(T_e^{-1} - T_n^{-1})]\} \\ & + S_{21}\{1 - \exp[227.7(T_e^{-1} - T_n^{-1})]\}\big) \quad , \end{aligned} \tag{15}$$

where $D = 5 + \exp(-326.6\, T_n^{-1}) + 3\exp(-227.7\, T_n^{-1})$, the units of T_e and T_n are K.

If we consider conditions when

$$372\,(T_e - T_n) \ll T_e T_n \quad , \tag{16}$$

and take into account that $99\, S_{10} \ll 327\, S_{20} + 228\, S_{21}$ then from Eq. (15) it follows that

$$L = \mathrm{N}_e[\mathrm{O}] f(T_n)(T_e - T_n)\, T_e^{-1}\, T_n^{-1} \quad , \tag{17}$$

where $f(T_n) = 8.132 \cdot 10^{-9} D^{-1}\,\mathrm{eV\,K\,cm^3\,s^{-1}}$.

The electron and neutral temperature dependencies of our cooling rate given by Eq. (17) can be compared with those of the Dalgarno (1969) cooling rate which is an analytical representation of the fine structure cooling rate derived by Dalgarno and Degges (1968):

$$L(D) = 3.4 \cdot 10^{-12}\ \mathrm{N}_e[\mathrm{O}](T_e - T_n)(1 - 7 \cdot 10^{-5}\, T_e)\, T_n^{-1} \quad . \tag{18}$$

It is seen that the ratio $(T_e - T_n)T_e^{-1}$ determines the electron temperature dependence of the oxygen fine structure cooling rate in the approach of Eq. (17), while $L(D)$ is proportional to $(T_e - T_n)(1 - 7 \cdot 10^{-5}\, T_e)$. The function $f(T_n)$ determines the difference in the neutral temperature dependencies of the oxygen fine structure cooling rates given by Eq. (17) and Eq. (18).

Let us compare the new oxygen fine structure cooling rate, $L(PB)$, calculated from Eqs. (12)–(15) by the use of the effective collision strengths of Bell *et al.* (1998) with the oxygen fine structure cooling rates, $L(TH)$ and $L(LN)$, given by Eqs. (2), (5), (7) which are based on the effective collision strengths of Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976), respectively, and currently used in models of the ionosphere. The convenient measure of the importance of the new effective collision strengths of Bell *et al.* (1998) for the electron cooling rate are the ratios $L(TH)/L(PB)$ and $L(LN)/L(PB)$. The fine structure cooling rate depends on two temperatures T_e, and T_n. The 800 K and 1200 K neutral temperatures are typical for solar minimum and maximum at the F2 region altitudes of the ionosphere and Fig. 2 shows the calculated ratios $L(TH)/L(PB)$ (curves 1) and $L(LN)/L(PB)$ (curves 2) as functions of $T_e - T_n$ for $T_n = 800\,\mathrm{K}$ (solid lines) and $T_n = 1200\,\mathrm{K}$ (dashed lines). Both ratios $L(TH)/L(PB)$ and $L(LN)/L(PB)$ increase with the increase of $T_e - T_n$. The value of the ratio $L(TH)/L(PB)$ is about 2–3 for $400\text{–}800 \le T_e - T_n \le 2000\text{–}2400\,\mathrm{K}$ and $T_n = 800\text{–}1200\,\mathrm{K}$, while the value of the ratio $L(LN)/L(PB)$ is about 2.5–4.0 for $240\text{–}640 \le T_e - T_n \le 1900\text{–}2300\,\mathrm{K}$ and $T_n = 800\text{–}1200\,\mathrm{K}$.

There is no direct measurements of these effective collision strengths or cross sections which determine the value of the oxygen fine structure cooling rate, although indirect measurement through the plasma heating experiment of Carlson and Mantas (1982) suggested that the cooling rate should be smaller than published rates of that time. There is also some evidence that the currently accepted fine structure cooling rates given by Hoegy (1976) and Carlson and Mantas (1982) may be too high by a considerable factor. This evidence comes from the comparison of the measured and modeled 63-μm atomic oxygen emission profile in the thermosphere (Grossman and Offerman, 1978).

The fine structure cooling rate given by Hoegy (1976) is larger than those of Carlson and Mantas (1982) as a result of the differences in the approximations of the collision strengths of Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976) (especially for the lower energy region which corresponds to the range of electron temperatures in the ionosphere). In the absence

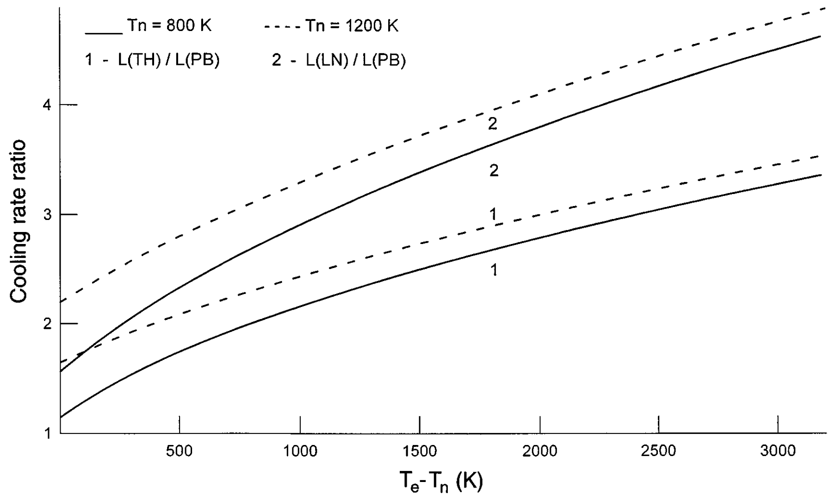

Fig. 2. Ratios of the fine structure cooling rate calculated by the use of the effective collision strengths of Tambe and Henry (1974, 1976) (*curves 1*) and Le Dourneuf and Nesbet (1976) (*curves 2*) with respect to the new oxygen fine structure cooling rate given by Eqs. (12)–(15) and based on the effective collision strengths of Bell *et al.* (1998) for $T_n = 800$ K (*solid line*) and $T_n = 1200$ K (*dashed line*)

of experiments which can discriminate between the theories, we have to rely on the quality of the scattering models employed in the theoretical calculations. Bell *et al.* (1998) used more accurate value of the dipole polarizability which is essential to account for long range electron-atom effects, and this is a significant improvement on all other calculations. Further, Bell *et al.* (1998) included extensive configuration interaction, essential to account for short range effects, as well as explicit inclusion of fine structure splitting; thus all important features of the scattering are accounted for. Figure 2 shows that the cooling rate given here represents the lowest of the calculated fine structure cooling rates and is more accurate than those of Hoegy (1976) and Carlson and Mantas (1982) as a result of the most sophisticated theoretical approach in the calculations of the collision strengths (see earlier).

4 Electron cooling rates

The relative magnitudes of the cooling rates are of particular interest for understanding of the main processes which determine the electron temperature. In this work we perform an examination of the electron cooling rates at Millstoune Hill on 7 and 9 April, 1990. These days are a part of the geomagnetically quiet and disturbed period on 6–12 April, 1990, at moderate solar-activity conditions which was studied by Pavlov (1998c) by comparison of the results from the IZMIRAN time-dependent mathematical model of the Earth's ionosphere and plasmasphere with the Millstone Hill incoherent-scatter radar measurements of electron density and temperature given by Buonsanto *et al.* (1992). The model used in this study is the last version of the IZMIRAN model presented by Pavlov (1998c) with the use of the new oxygen fine structure cooling rate given by Eqs. (12)–(15).

Figure 3 shows calculated altitude profiles of the electron cooling rates, L_s at 12.00 LT during quiet conditions 7 April, 1990, (left panel) and geomagnetically storm period on 9 April, 1990, (right panel) from the updated version of the IZMIRAN model of the Earth's ionosphere and plasmasphere. The energy exchange between the electron and ion gases (curve 6) is the largest cooling channel above 230 km on 7 April,

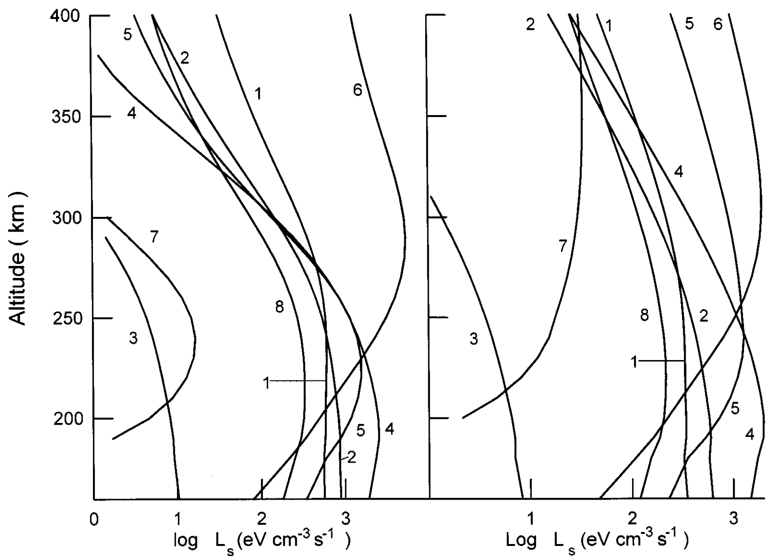

Fig. 3. Computed altitude profiles of electron cooling rates L_s at 12.00 LT on 7 April, 1990, (*left panel*) and 9 April, 1990, (*right panel*). *Line 1* gives the cooling due to fine structure excitation of atomic oxygen. The cooling rates by rotational excitation of N_2 and O_2 are shown by *curves 2 and 3*. The cooling rates by vibrational excitation of O_2 and N_2 are shown by *curves 4 and 5*. *Line 6* shows the cooling due to Coulomb collisions electrons with ions and *line 7* represents the electron cooling rate in collision of $O(^3P)$ with thermal electrons with the $O(^1D)$ formation. The total elastic cooling rate by elastic collisions of electrons with N_2, O_2, O, He, and H is shown by *curve 8*

1990, and 250 km on 9 April, 1990. The energy exchange between the electron and ion gases (curve 6), the revised electron cooling rates by vibrational excitation of O_2 (curve 4) and N_2 (curve 5) given by Pavlov (1998a, c) are the largest cooling rates above 160 km. The fine structure cooling by O (curve 1) calculated from the expressions (12)–(15), the electron cooling rate by rotational excitation of N_2 (curve 2) revised by Pavlov (1998a), and the total elastic electron cooling rate due to elastic collisions of electrons with N_2, O_2, O, He, and H (curve 8) presented by Schunk and Nagy (1978) are less that the sum of the mentioned cooling rates given by curve 4, 5, and 6 of Fig. 3, and these results are valid during daytime for all geomagnetically quiet and disturbed periods on 6–12 April, 1990. The cooling of thermal electrons from rotational excitation of O_2 (curve 3) revised by Pavlov (1998b) and the cooling rate in collision of $O(^3P)$ with thermal electrons with the $O(^1D)$ formation (curve 7) given by Pavlov (1997) are not important in calculations of T_e, and we found that these conclusions are valid during daytime and night-time conditions for the geomagnetically quiet and disturbed period on 6–12 April, 1990. We evaluated the role of the electron cooling rates by low-lying electronic excitation of $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g^+)$ (Prasad and Furman, 1973) and found that in agreement with the conclusions of Pavlov (1998b) the effect of these cooling rates on the electron temperature can be considered negligible for the geomagnetically quiet and disturbed period on 6–12 April, 1990.

Figure 4 compares the new oxygen fine structure cooling rate calculated from Eqs. (12)–(15) (curves 4) with the early result of Dalgarno (1969) given by Eq. (18) (curves 1) and the oxygen fine structure cooling rates, $L(TH)$ (curves 2) and $L(LN)$ (curves 3), given by Eqs. (2), (5), (7) which are based on the effective collision strengths of Tambe and Henry (1974, 1976) and Le Dourneuf and Nesbet (1976), respectively. The cooling rate profiles of Fig. 4 are calculated at 12.00 LT on 7 April, 1990 (solid lines) and 9 April, 1990 (dashed lines). The IZMIRAN model electron densities and temperatures with the use of the new oxygen fine structure cooling rate given by Eqs. (12)–(15) were used for calculations of all cooling rates of Fig. 4. It is seen that the fine structure cooling rate given by Dalgarno (1969) is the largest cooling rate while that obtained in this work is the lowest cooling rate in comparison with the earlier mentioned approaches. The value of $L(LN)$ is larger than the value of $L(TH)$ by a factor of 1.34–1.36. The new cooling rate we found is less than $L(TH)$ by a factor of 1.5–2.6 in the altitude range 160–400 km. Figure 4 shows that the difference between the model atomic oxygen neutral densities and electron densities and temperatures calculated on 7 April (undisturbed period) and 9 April (negative ionospheric storm) significantly affects the electron cooling rates that are our subject.

We found that the difference between the oxygen fine structure cooling rates calculated by the use of the simple approach given by Eq. (17) and the rigorous approach of Eqs. (12)–(15) is less than 5% at 12.00 LT on 7 April, 1990, and 9 April, 1990. The use of the simple approach of Eq. (17) in the IZMIRAN model leads to negligible changes in the electron temperature (up to 5 K) at the F2-peak altitude 1990 in comparison with T_e calculated by using the rigorous approach of Eqs. (12)–(15) for the period of 6–12 April.

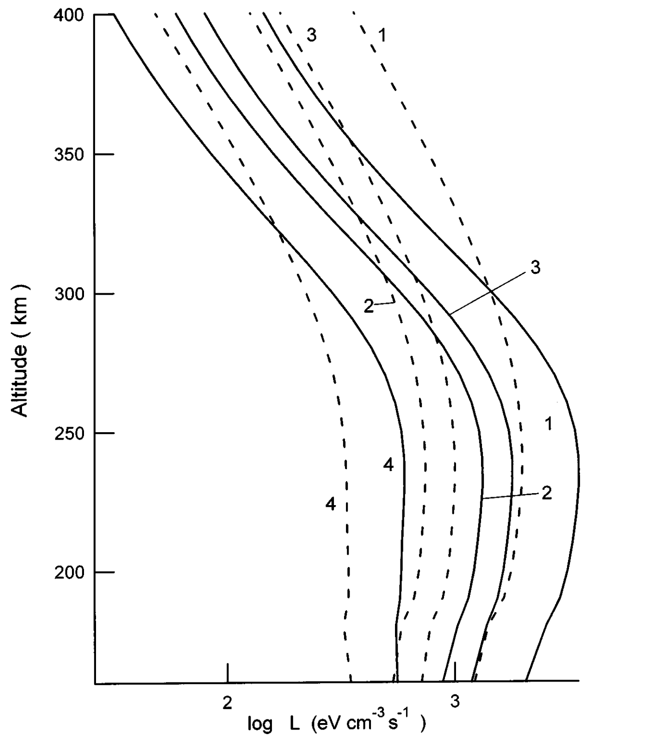

Fig. 4. Comparison of cooling rates due to fine structure excitation of atomic oxygen at 12.00 LT on 7 April, 1990 (*solid lines*) and 9 April, 1990 (*dashed lines*) given by Dalgarno (1969) (*curves 1*) and calculated by the use of the effective collision strengths of Tambe and Henry (1974, 1976) (*curves 2*) and Le Dourneuf and Nesbet (1976) (*curves 3*) with the oxygen fine structure cooling rate found here, (*curves 4*) which is based on the effective collision strengths of Bell *et al.* (1998)

The inclusion or exclusion of the oxygen fine structure cooling rate in calculations of electron and ion densities and temperatures can illustrate the role of this cooling rate in the ionosphere. It was found that the elimination of the oxygen fine structure cooling rate from the IZMIRAN model leads to an increase of up to about 60 K of the calculated electron temperature at the F2-peak altitude for the period of 6–12 April, 1990. The F2 peak electron density is decreased by about 1% as a result of a respective increase in T_e.

5 Conclusions

Recent advances in the collision-strength calculations of Bell *et al.* (1998) for electron impact excitation of the ground-state ^3P fine-structure levels in atomic oxygen have made possible more accurate determination of the atomic oxygen fine structure cooling rate of thermal electrons. The new effective collision strengths of Bell *et al.* (1998) have been fitted to analytical expressions and the fine structure cooling rate based on these collision strengths is given in an analytical form of Eqs. (12)–(15) which is available to the researcher for quick reference and accurate computer modelling with a minimum of calculations. Numerically, the new cooling rate is less than the value of $L(TH)$ by a factor of about 2–3 for $400–800 \leq T_e - T_n \leq 2000–2400$ K and $T_n =$ 800–1200 K, while the value of the ratio $L(LN)/L(PB)$ is about 2.5–4.0 for $240–640 \leq T_e - T_n \leq 1900–2300$ K and $T_n = 800–1200$ K. It would be desirable if cross sections for electron impact excitation of the ground-state ^3P fine-structure levels in atomic oxygen could be measured experimentally, thus assisting in determining the accuracy of the results presented in this paper. As there are no such measurements, the cooling rate given here represents the lowest of the calculated fine structure cooling rates and is more accurate than those of Hoegy (1976) and Carlson and Mantas (1982) as a result of the most sophisticated theoretical approach in the calculations of the collision strengths.

To perform an examination of the electron cooling rates we used an enhanced and updated version of the IZMIRAN model of the Earth's ionosphere and plasmasphere that we have steadily developed over the years. The enhancement to the IZMIRAN model developed in this study is the use of the new oxygen fine structure cooling rate given by Eqs. (12)–(15). We found that at Millstoune Hill during daytime for the geomagnetically quiet and disturbed period on 6–12 April, 1990, at moderate solar-activity conditions the energy exchange between the electron and ion gases and the electron cooling rates by vibrational excitation of O_2 and N_2 are the largest cooling rates above 160 km. The fine structure cooling by O and the electron cooling rate by rotational excitation of N_2 are less than the mentioned cooling rates. We evaluated the role of the electron cooling rates by low-lying electronic excitation of $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g^+)$, from rotational excitation of O_2, and in collision of $O(^3P)$ with thermal electrons with the $O(^1D)$ formation, and found that the effect of these cooling rates on the electron temperature can be considered negligible for the geomagnetically quiet and disturbed period on 6–12 April, 1990. We found that the elimination of the oxygen fine structure cooling rate from the IZMIRAN model leads to an increase of up to about 60 K of the calculated electron temperature at the F2-peak altitude for the period of 6–12 April, 1990, and these calculations show that the role of this cooling rate is not significant as the F2-peak altitudes of the ionosphere.

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